# Controlled Drift of Indirect Excitons in Coupled Quantum Wells: Toward Bose Condensation in a Two-Dimensional Trap

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We have succeeded in trapping indirect excitons in coupled quantum wells in a harmonic potential minimum via inhomogeneous applied stress and electric field. These excitons exhibit a strong Stark shift (over 60 meV), long lifetime (100 ns), and high diffusivity (1000 $cm^2/s$). This approach is very promising for obtaining the high exciton density needed for Bose condensation of excitons in two dimensions.

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Over the past 15 years, several experiments have indicated evidence of Bose effects or Bose condensation of excitons in semiconductors [1–13]. These experiments mostly fall into four basic categories: evidence based on spectral lineshape analysis following incoherent generation of the excitons, which shows narrowing of the exciton luminescence lines at high densities [1,2,4,5,7], evidence based on comparison of total luminescence intensities of two different excitonic species, by which the relative populations can be deduced [3,13], evidence based on light emission following coherent generation of excitons in the ground state, which shows that excitons remain in regions of phase space near the ground state for time periods long compared to the exciton scattering time [6,11,12], and measurements of the transport of the excitons which show fast expansion out of the creation region [3,9,10]. This body of evidence, while important, lacks the dramatic "smoking gun" that has been seen in alkali atoms in magneto-optical traps [14,15], namely, a *spatial* condensation into a two-component distribution, a clear prediction of the theory of the weakly interacting Bose gas which has no classical analog. It has long been known [16] that excitons in a harmonic potential will also show this behavior if they undergo Bose condensation; a method of creating a harmonic potential for excitons in bulk semiconductors is well established [16], but so far, experimental attempts with bulk semiconductors have not succeeded in creating a density of excitons high enough for Bose condensation in this kind of trap.

Much recent attention has been given to indirect, or "dipole," excitons in two-dimensional heterostructures [7–9,17–20]. This system is appealing because (1) the excitons can have long lifetimes due to the spatial separation of the electron and hole, (2) the interaction between the dipole-aligned excitons is strongly repulsive, so that crossover to a Fermi liquid state is not expected at high density, and (3) the quality of semiconductor heterostructures has been steadily increasing, so that true two-dimensional physics can be studied. In a two-dimensional system, Bose-Einstein condensation is not expected, but rather a Kosterlitz-Thouless transition to a superfluid state [21], although J. Fernández-Rossier, C. Tejedor, and R. Merlin [22] have recently argued that the coupling of the excitons to the photon states will allow them to undergo Bose condensation in two dimensions.

Early experiments with this type of structure [7] showed evidence for Bose effects, but later work [18] showed that localization due to random variations in the structures significantly complicated the analysis of the luminescence lineshape. Recent studies of similar stuctures [8,9] have shown quite promising results, including evidence for increased diffusion out of the excitation region at high density and low temperature. Other recent measurements of the diffusion of indirect excitons have also shown fast expansion at high densities [20]. Enhanced diffusion is expected for superfluid excitons, but can also be attributed to other, classical effects which also occur at high density, such as phonon wind [23].

In order to overcome the complications of localization and classical, pressure-driven expansion, X.J. Zhu, P.B. Littlewood, and T.M. Rice [19] proposed a variation in which *inward pressure* on the excitons is produced which confines them to a potential minimum. As Nozierés [24] and others have pointed out, if a potential minimum exists, true Bose condensation can occur in two dimensions instead of a Kosterlitz-Thouless transition. Zhu, Littlewood, and Rice envisioned that a potential minimum could be created by a variation in the quantum well thickness. In this Letter, we report the experimental accomplishment of a potential minimum for indirect excitons in a two-dimensional plane via a different means. This method creates a harmonic potential minimum for the excitons, so that the telltale two-component spatial signature of Bose condensation can occur, and it allows

us to vary the depth of the potential minimum via an external control.

The samples we use are $GaAsAl_xGa_{1-x}As$ coupled quantum well structures fabricated via molecular-beam epitaxy (MBE) at the Max-Planck-Instutute in Stuttgart; the substrate is heavily p-doped and the capping layer is heavily n-doped in order to allow electric field perpendicular to plane of the quantum wells. Fig. 1(a) illustrates the band structure when electric field is applied; as seen in Fig. 1(b), as the electric field is increased, the energy of the indirect excitons undergoes a strong Stark shift to lower energy, as also seen in previous studies (e.g., Refs. [25,26].) The spatial separation of electron and hole into two separate planes also increases the lifetime of the excitons; in our samples we measure lifetimes of the indirect excitons of around 100 ns.

We create a potential minimum for the excitons via externally applied, inhomogeneous stress and electric field. Fig. 2 shows the experimental geometry. The quantum well sample is clamped between two metal plates, each with a small hole, and a pin is pressed against the GaAs substrate, which has been polished on both surfaces prior to the MBE fabrication. The pin creates a shear strain maximum in the quantum wells, as well as a slight hydrostatic expansion; both of these strain effects lead to an energy minumum for the excitons via the Pikus and Bir deformation Hamiltonian [27], similar to the way in which inhomogeneous strain leads to a potential energy minimum for carriers in bulk semiconductors [16,28,29]. Too much stress from the pin will cleave the sample, of course, but springs on the back of the sample help to prevent this, allowing a reproducible, controllable stress.

In addition, the pin is held at a fixed, negative voltage while the clamping plates are connected to ground. This causes a current to flow through the heavily-doped substrate, so that the voltage across the quantum wells drops to zero far away from the pin. As seen in Fig. 1, higher electric field corresponds to lower energy for the indirect excitons, so that this effect also contributes to a potential energy minimum for the excitons below the pin.

The entire assembly is placed in liquid or gaseous helium, and the quantum wells are excited by a laser through the window of an optical cryostat by means of a prism attached to the lower metal plate. The force on the pin is controlled by a micrometer at the top of the cryostat, as in Ref. [29]. Fig. 3 shows time-integrated luminescence from a coupled quantum well sample with 60 Å GaAs wells and 42 Å $Al_{.3}Ga_{.7}As$ barrier, taken with a CCD camera on the back of an imaging spectrometer as the laser spot is scanned across the surface of the sample. As seen in Fig. 3(a), a well depth of more than 10 meV can be created, compared to the inhomogeneous broadening in these samples of slightly less than 1 meV. When the voltage applied to the pin is set to zero, the same time-integrated scan gives Fig. 3(b), which shows that the effect of the variation in voltage is about the same as the effect of the shear strain maximum.

The fact that a potential minimum occurs is strongly connected to the geometry which leaves the lower surface of the sample unconstrained. When the sample is placed on a glass slide, a potential energy *maximum* is seen, since in this case the sample is compressed, and the positive shift in energy due to the hydrostatic deformation potential overwhelms the negative shift due to shear strain. We have solved the static field equations for strain in the sample via finite-element analysis, and the shifts in energy in both cases agree with our calculations [30].

In a harmonic potential minimum in two dimensions, the critical number for Bose condensation is given by

$$\begin{aligned} N_c &= \sum_n n \frac{1}{e^{n\hbar\omega/k_BT}-1} \\ &= \frac{(k_BT)^2}{(\hbar\omega_0)^2}\int \epsilon d\epsilon \ \frac{1}{e^\epsilon - 1} \\ &= 1.8\frac{(k_BT)^2}{(\hbar\omega_0)^2}, \end{aligned} \tag{1}$$

where $\omega_0 = (\alpha/m)^{1/2}$. The shape of the well shown in Fig. 3(a) corresponds to a force constant of $\alpha = 65$ meV/mm$^2$, approximating $U = \alpha x^2/2$ in the center of the trap. For a temperature of 2 Kelvin and exciton mass on the order of the electron mass, this critical number is approximately $10^7$. By comparison, a single laser pulse from our dye laser contains more than $10^{11}$ photons. We have not seen evidence for Bose effects in this well, however. Because we excite at $\lambda = 660$ nm, the excess energy of the generated carriers is quite high, so that the carrier temperature is well above 100 K for most of their lifetime, as determined by fits to the band-edge luminescence from the substrate at the same times, even when the sample is immersed in liquid helium. At this temperature, the critical number is four orders of magnitude higher.

The diffusion length of the excitons is also too short for thermalization in the well at this temperature. Fig. 4 shows the spatial profile of the indirect exciton luminescence at various times after a laser pulse has created them about 400 $\mu$m from the center of the well. The expansion at early time corresponds to a diffusion constant of over 1000 cm$^2$/s, similar to that of Ref. [20]. (This fast expansion at early time is essentially the same even with zero applied stress.) At late times, as the exciton density drops, the expansion of the excitons slows down, although the effect of drift due to the gradient in potential energy is clearly seen.

For a lifetime of 100 ns and D = 1000 cm$^2$/s, the diffusion length of the excitons is around 100 $\mu$m. By comparison, the equilibrium spatial width of a classical gas in a harmonic potential well with $\alpha = 65$ meV/mm$^2$, determined approximately by the condition $\alpha x^2/2 = 3k_BT/2$ [16], is over 500 $\mu$m.

As the exciton gas gets colder, the equilibrium spatial width should become smaller, to less than 100 $\mu$m at 2 K. This also indicates the importance of lower effective exciton temperature. We believe that by creating the excitons with lower energy via near-resonant excitation, we can significantly reduce the exciton temperature in the future.

Another approach which may also aid the approach to Bose condensation of excitons in this geometry may be adding a strong magnetic field, which will reduce the spin degeneracy of the excitons, forcing higher numbers of particles into few states, and which will also create a more strongly repulsive interaction between the excitons. Several authors [31–33] have argued that magnetic field will enhance Bose effects of excitons; experimentally, Ref. [9] reported a sharp increase of diffusivity of indirect excitons above a critical threshold of magnetic field.

Recently, several authors [22,34,35] have proposed optical tests for the phase coherence which should appear in the excitonic Bose condensate. Underlying all these approaches is the fact that Bose condensation implies spontaneous phase coherence, and since excitons couple to photon states, this phase coherence should transfer to the photons, even in the absence of lasing. The method proposed here of confining an exciton condensate to a trap is much more amenable to these kinds of tests than methods which allow free expansion of the exciton gas, since the ground state in this case is well defined.

Finally, we note that the method we have used here to trap the excitons may have other applications. Since excitons are charge neutral, they do not respond to electric field, and it is therefore difficult to control their motion. We have shown that the motion of excitons in heterostructures can be controlled over distances up to 100 $\mu$m via both inhomogeneous shear stress and inhomogeneous electric field. In particular, variation of the voltage across the quantum wells can be accomplished by depositing resistive patterns on the surface via photolithography. Small "wires" for excitons can therefore be created which carry excitons from place to place in response to electric fields.

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FIG. 1. (a) Band structure of the coupled quantum well structures used in this experiment. Indirect excitons are formed from electrons in the lowest conduction subband and the highest valence subband. (b) Peak photon energy of the two luminescence lines from the structure, as a function of reverse bias voltage. Solid circles: indirect (interwell) excitons, open circles: direct (intrawell) excitons. The intensity of the intrawell excitons relative to the interwell excitons first falls, then rises as the electric field is increased.

FIG. 2. Exerimental geometry for applying inhomogeneous strain and electric field to the samples. The pin is pressed against the sample with approximately 5 lb. of force.

FIG. 3. (a) Time-integrated image through an imaging spectrometer of the indirect exciton luminescence as the laser spot is scanned across the surface of the quantum well sample with 43 kV/cm applied field. The point of lowest energy corresponds to the point directly below the tip of the pin shown in Fig. 2. (b) Time-integrated image for the same conditions but zero applied field. As seen in this comparison, the inhomogeneous electric field gives a contribution to the trap as large as that of the applied shear stress.

FIG. 4. Spatial profiles of the luminescence from the coupled quantum well structure at various times after a short (5 ps) laser pulse. The laser is focused about 400 $\mu$m from the center of the trap shown in Fig. 3. As seen in this figure, the indirect excitons drift toward the center of the well due to the gradient in potential energy. The expansion at early time, before 50 ns, corresponds to a diffusion constant of 1000 $cm^2/s$.

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